A NUMERICAL SIMULATION OF IMPACTS INTO GRANULAR MATERIALS BY DISTINCT ELEMENT METHOD. K. Wada, *Department of Earth and Planetary Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan (wada@sys.eps.s.u-tokyo.ac.jp)*, H. Senshu, *Institute for Frontier Research on Earth Evolution, Japan Marine Science and Technology Center, 2-15, Natsushima-cho, Yokosuka, 237-0061, Japan*, S. Yamamoto, T. Matsui, *Graduate School of Frontier Sciences, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan*.

Introduction: Hydrocode simulations have been performed to reveal the nature of the cratering processes(e.g. [1]). In the hydrocode simulations, materials are treated as continuum. This is not appropriate for the analysis of motion of ejecta due to impacts into granular materials.

A numerical simulation method called Distinct Element Method (DEM) has been developed in the field of powder technology to reveal the behavior of granular materials (e.g. [2]). Since materials are treated as distinct elastic particles in this simulation, this method has a potential benefit to simulate the cratering process on granular materials and the behavior of ejecta.

Therefore, using DEM we conducted a numerical simulation of impact into granular material. We can derive the velocity distribution of ejecta. Then, we compare the numerical results with the scaling laws obtained from impact experiments[3-7]. Using these comparisons we try to evaluate whether or not DEM simulation can be used to model processes of ejecta ejection due to impacts into granular materials.

Description of DEM: In DEM, particles are considered as hard spheres but are permitted to overlap a little bit each other. The motion of each particle is calculated by two steps: the mechanical interactions between contact particles are calculated for the overlapping length, and then the translational and rotational motions of particles are calculated by solving the equation of motion of each particle. The mechanical interactions between particles are assumed to be expressed by elastic forces and friction, modelled by the Voigt-model. These interactions are essentially parameterized by the coefficients of restitution e and friction μ. It should be noted that the friction calculated here is not static but kinetic. This means that we cannot calculate the final crater shape in our simulations. Therefore we will use the radius of transient craters as the crater radius.

Simulation Setting: We developed a 3-D DEM code to simulate a vertical impact on a granular target. As a granular target, we use 384000 equal-sized particles (radius; 1mm, density; 2g/cm^3, Young's modulus; 75GPa, and Poisson's ratio; 0.25) randomly placed in a rectangular container with sidelength of 20cm and height of 7cm. The porosity of the target is about 43%. e of walls of the container are set to 0 so that the reflection waves cannot be generated at the walls. An impactor particle (density; 2.7g/cm^3, Young's modulus; 70GPa, and Poisson's ratio; 0.35) with radius of 2 and 5 times that of a target particle impacts vertically into the target at velocities of 100m/s and 300m/s. These velocities are comparable to or less than the sound velocity of granular materials. Various values of e and μ of particles are used in the simulations, although we use $e = 0.4$ and $\mu = 0.25$ as a representative value. Tracing the motion of each particle, we can determine the transient crater radius and the ejection velocity distribution.

Results: Our simulations suggest that the numerical results are independent of the values of e and μ. Thus we show the results only for the representative case ($e = 0.4$ and $\mu = 0.25$) hereafter.

Fig.1 shows a snapshot of the transient crater (to show clearly the cross section, only the particles located along the cross section are delineated). A bowl-shaped crater and particles forming ejecta curtain can be seen.

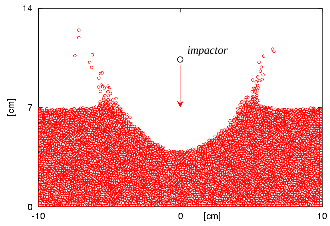

Figure 1: A snapshot (40 ms after impact) of the transient crater formed by 300m/s impact.

The transient crater radii R are measured for the simulations of various sets of parameters. Then we can evaluate the π-group scaling parameters[3]; that is, the dimensionless crater radius π_R defined by $R(\rho_t/m)^{1/3}$, where ρ_t is the target bulk density and m is the impactor mass, and the dimensionless gravity-scaled size π_2 defined by $3.22ga/V_i^2$, where g is the gravitational acceleration, a is the impactor radius and V_i is the impact velocity. In Fig.2 are plotted these results and the scaling laws obtained from the impact experiments[3,4]. Since the particles in our simulations are assumed to be cohesionless, we use the scaling laws in the gravity regime. As shown in Fig.2, the normalized crater radii obtained in our simulations are close to the line of the scaling laws for dry sands (although a little bit higher for π_R).

The data on the velocities and positions of all particles ejected from the target surface are recorded during the simulations. Then, we can plot the ejection velocity v_e normalized by $\sqrt{gR}$ against the distance x from the

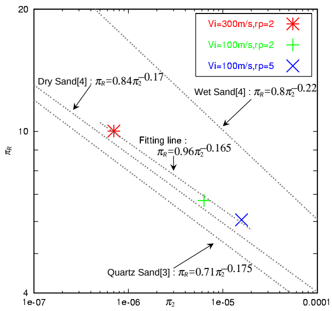

Figure 2: Dimensionless crater radius π_R versus dimensionless gravity-scaled size π_2 for various impact conditions.

impact point to the ejection point normalized by R. A typical result of our simulations is shown in Fig.3. As predicted by Housen et al.[5], the normalized ejection velocities seem to have a linear correration in log-scale plots with the normalized ejection positions. We can see a trend that the ejection velocity decreases as the ejection position from the impact point increases. The slope of the line fitted to the data, (that is, the power-law exponent) in Fig.3 is -2.46. This is similar to that of the scaling laws obtained from the explosion experiments; -2.55, and that estimated theoretically from the impact experiments on dry sands; -2.44[5].

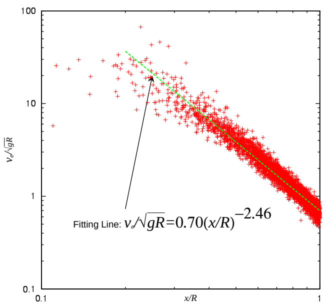

Figure 3: The normalized ejection velocity versus the normalized ejection position for 300m/s impact (impactor radius is 2 times that of a target particle).

We show another plots of the data on the ejection velocity distribution, that is, the relation between the normalized volume of ejecta with velocity greater than a given ejection velocity, $V(> v_e)/R^3$, and the normalized ejection velocity, $v_e/\sqrt{gR}$. Our results and the data obtained from the explosion[6] and impact experiments[7], and also the estimated scaling law[5], $V(> v_e)/R^3 = 0.32(v_e/\sqrt{gR})^{-1.22}$, based on the experimental data[5] are plotted in Fig.4. As shown in this figure, the slope of our simulation is similar to that of the experiments. The absolute values of $V(> v_e)/R^3$ of the simulation data are, however, below those of the experiments. This discrepancy will be discussed later. In the region of higher ejection velocities, the slope of our simulation becomes steep, which implies smaller amount of ejecta with higher velocities and existence of an upper limit for the normalized ejection velocity[8,9].

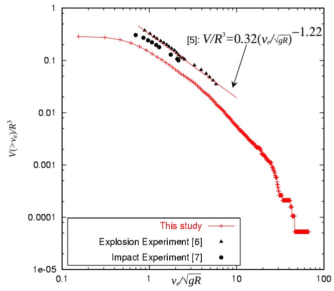

Figure 4: The normalized volume of ejecta with a velocity greater than a given ejection velocity versus the normalized ejecta velocity for 300m/s impact (impactor radius is 2 times that of a target particle).

Discussion: The discrepancies between our simulation and the laboratory experiments shown in Fig.2 and 4 could be interpreted as follows. Our simulations would make a crater radius larger than that formed in experiments. The larger crater radius results in the higher value of π_R in Fig.2 and the lower value of V/R^3 in Fig.4. The reason why the crater radius becomes larger in our simulations would be as follows: (1) the static friction, which is an important factor for the crater shape, is not included in our simulations, (2) the particles in our simulations are not permitted to be deformed or fragmented and thus the energy consumed in a real situation by the fragmentation of particles would be partitioned to the kinetic energy of the particles in our simulation, and (3) all particles are spheres and the asymmetric form of particle that may cause excess dissipation of energy is not taken into account in our simulations.

No significant changes can be seen in the results with the various values of e and μ of particles. This implies that the ejection of particles is mainly due to flow, not collisions among particles. Therefore, it can be said that the excavation flow in cratering process is expressed well in the DEM calculation.

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References:

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